

Notes on Hydraulic Systems

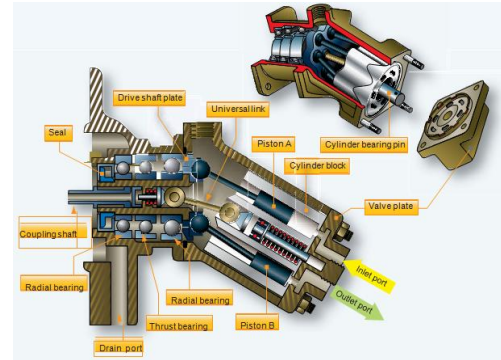
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The accompanying material on Hydraulic Systems (HS) is intended to cover the syllabus of the V Unit of the subject 'Hydraulic Machines & Systems' for BE III (Mech.) of OU.

It also helps to introduce the area to beginners.

Hydraulic systems find extensive applications in industry. As such the evolution has seen a great variety of pumps, valves and circuits including very complex ones. The notes provides a brief coverage of the working principles of major components and circuits used in hydraulic systems, and deals with:



- i. What and why of hydraulic systems
- ii. Pumps used in HS
- iii. Accessories – Filters, Accumulators, Heat exchangers
- iv. Commonly used Directional and Pressure control valves
- v. Important hydraulic circuits.
- vi. Hydraulic Servo Systems

Acknowledgement: The material, particularly diagrams, is collected from the following sources:

- a. [www.nitc.ac.in/dept/me/jagadeesha/fluid power](http://www.nitc.ac.in/dept/me/jagadeesha/fluid%20power)
- b. www.yukenindia.com/hydraulicstraining
- c. www.faa.gov/.../handbooks_manuals/aircraft/...handbook/
- d. "The Control of Fluid Power", Longman by D McCloy and HR Martin.

HYDRAULIC SYSTEMS

1. Introduction

Hydraulic systems are used for transmission of power through the medium of hydraulic oil. The hydraulic system works on the principle of Pascal's law which says that “ *the pressure in a fluid at rest is transmitted uniformly in all directions*” .

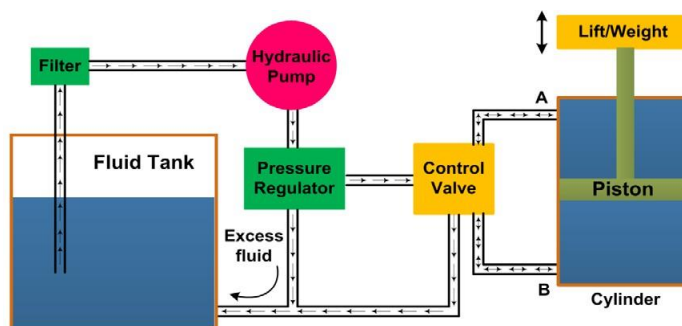
The fluid medium used is hydraulic oil, which may be mineral oil or water or combinations. This area is also known as oil hydraulics.

The power transferred is

Power = Pressure x flow rate in the tubes or hoses.

The schematic of a simple hydraulic system is shown in the figure below. It consists of:

- a movable piston connected to the output shaft in an enclosed cylinder
- storage tank containing hydraulic fluid
- filter which is in suction line of pump inside the tank or on tank inlet line.
- Electric motor / Diesel or petrol engine which is the primary source of power
- Hydraulic pump driven by motor or engine
- Pressure control valve
- Leak proof closed loop piping.
- Direction control valve which controls the direction of fluid flow so as to change the direction of motion of a linear or rotary actuator
- Actuator – A cylinder for linear movement or a hydraulic motor for rotary actuation of load



1.1 Applications of Hydraulic Systems

The chief advantage that hydraulic systems derive is from the high pressures that can be applied leading to high force or torque by the actuating piston or motor.

Pressures normally used in Industry are 140 bar (140 kgf/ cm² \approx 14 MPa \approx 2000 psi). But in some specific applications in machine tools and aerospace, 350 bar (35 MPa or 5000 psi) is also common.

Example: Consider an actuator with a 10 cms diameter piston. If the pressure applied on the piston is 140 bar, Force that the piston rod delivers

$$= F = \text{Pressure} \times \text{Area} = 140 * \pi/4 * 10^2 = 10,996 \text{ Kgf} = 108 \text{ KN.}$$

ie nearly 10 Tons of load can be applied using a 10 cms dia cylinder. If the pressure is 350 bar, load will be 25 Tons.

Similarly high torques can be applied with a small sized motor compared to an electric motor. The high Power / Weight ratio of the hydraulic actuators is the prime reason for use of hydraulics.

1.2 Application areas:

Hydraulic systems are generally used for precise control of larger forces. The main applications of hydraulic system can be classified in five categories:

Industrial: Plastic processing machineries, steel making and primary metal extraction applications, automated production lines, machine tool industries, paper industries, loaders, crushers, textile machineries, R & D equipment and robotic systems etc.

Mobile hydraulics: Tractors, irrigation system, earthmoving equipment, material handling equipment, commercial vehicles, tunnel boring equipment, rail equipment, building and construction machineries and drilling rigs etc.

Automobiles: brakes, shock absorbers, steering system, wind shield, lift and cleaning etc.

Marine applications: Controls in ocean going vessels, fishing boats and naval equipment.

Aerospace equipment: Rudder control, landing gear, brakes, flight control and transmission, rocket motor movement

1.3 Advantages and Disadvantages of Hydraulic systems

Advantages of Hydraulic systems

- High power to weight ratio compared to electrical systems
- Allows easy control of speed and position, and direction
- Facilitates stepless power control
- Allows combination with electric controls
- Delivers consistent power output which is difficult in pneumatic or mechanical drive systems
- Performs well in hot environment conditions

Compared to Pneumatics:

- Much stiffer (or rigid) due to incompressible fluid
- Better speed of response
- Better lubricity (less friction) and rust resistance
- Low maintenance cost.

Disadvantages

- **Material** of storage tank, piping, cylinder and piston can be **corroded** with the hydraulic fluid. Therefore one must be careful while selecting materials and hydraulic fluid.
- Structural **weight** and size of the system is **more** which makes it unsuitable for the smaller instruments.
- Small **impurities** in the hydraulic fluid can permanently damage the complete system. Therefore suitable filter must be installed.
- **Leakage** of hydraulic fluid is also a critical issue and suitable prevention method and seals must be adopted.
- Hydraulic fluids, if not disposed properly, can be harmful to the **environment**.

1.4 Relative advantages of different power transmission systems:

Each type of **power transmission and control system** has specifically suitable application areas. However, we can make some general comparisons between them.

Fluid power and Electrical are good at transmitting power over long distances, and also better controllable compared to mechanical devices. Electrical devices are the cheapest. Hydraulic systems have better power/weight ratio. In terms of cost, electrical would be the cheapest.

Following table gives a relative comparison of Hydraulic, pneumatic and Mech / EM systems .

H – Hydraulic; P – Pneumatic M – Mechanical/Electromechanical; E – Electrical

Property	Best	Good	Fair
<i>Torque/Inertia</i>	H	P	M
<i>Power /weight</i>	H,P	-	M
<i>Rigidity</i>	H	M	P
<i>Dirt vulnerability</i>	E,M	-	H,P
<i>Speed of response</i>	E	H	M, P
<i>Compactness</i>	E	H	M,P
<i>Ability to work in adverse conditions</i>	-	P,M,H	E
<i>Relative cost</i>	M,E	H,P	-

1.5 Hydraulic fluids:

The general requirements of fluids in power transmission are :

1. Low cost
2. Non-corrosive
3. Have infinite stiffness
4. Good lubrication properties
5. Store well without degradation
6. Non-toxic
7. Non-inflammable
8. Properties remain stable over wide range of temperatures.

Many types of fluids are used ranging from water, mineral oils, vegetable oils, synthetic and organic liquids. Water was the first liquid used and is very cheap. But its disadvantages are – freezes easily, rusts metal parts, boils and relatively poor lubricant. Mineral oils are far superior in these properties. Its success also lies in – the ease with which their properties can be changed with **additives**.

Additives used are - various chemicals like phenols and amines, chlorine and lead compounds, esters, organo-metallic compounds, for change in properties such as:

1. Antioxidants
2. Corrosion inhibitor
3. Rust inhibitor
4. Anti-foam
5. Lubrication improver
6. Pour point depressant
7. Viscosity index improver.

1.6 FILTERS

When hydraulic fluids are contaminated, hydraulic systems may get damaged and malfunction due to clogging and internal wear . They require filtration to remove contaminants.

Filters are classified as

- i. Reservoir filters:
- ii. Line filters
- iii. Off-line filters
- iv. Other cleaning equipment
 1. Reservoir filters: These may be installed in the reservoir at the pump suction port or in the return line cleaning the liquid returning to the port.
Suction type filter consists of a core rolled up with a filter paper and submerged in working fluid. Typically they use 100 micron filter papers.
Return filters are either mounted on the reservoir or in the lines.
Filtration ratings in return lines vary from 10 micron to 35 micron, lower micron rating being used for higher pressures.
 2. Line filters: These are installed when high filtration is required and are used to avoid high suction at the reservoir filters. These are used with a separate line connection. Filter selection depends upon pressure, flow rate and filtration rating.
 3. Off-line filters: These filters clean fluids in a reservoir using a dedicated pump and filter separate from the line. These are used when higher cleaning level is required.
 4. Other equipment include air breather (filtering out dust in the air), oil filling port or magnetic separator to absorb iron powders in reservoir.

1.7 ACCUMULATORS:

These are used to supply additional fluid when main line fluid pump is inadequate to perform the actuation. Usually gas filled bladders at high pressure act on the reservoir of fluid in the accumulator to make up for the required line flow.

Accumulators are used

- i. to accommodate large flow rates or to compensate leakages.
- ii. Absorb pulsations and reducing noise
- iii. To absorb shocks.

Types:

- i. Bladder type: Separates gas from oil by a rubber bladder
- ii. Diaphragm type: Sometimes used as a small accumulator
- iii. Piston type: Shaped as a cylinder without a rod
- iv. Spring type, weight loaded type.

1.8 HEAT EXCHANGERS:

Energy generated by prime movers transforms to thermal energy which increases the temperature of the working fluid. High temperatures deteriorate the fluid properties and result in shorter fluid life. Hence it is required to cool the oil to certain level for smooth operation.

Typical heat exchangers used are:

- i. Tubular heat exchangers: This delivers cooling fluid through copper tubes to accomplish heat exchange between fluid and cooling water.
- ii. Plate heat exchanger: This consists of many thin cooling plates which exchange heat with cooling water.
- iii. Air cooling radiator: Forced air flows through tubes and cools the fluid
- iv. Refrigerant exchanger: This is like a domestic refrigerator and dissipates heat from fluid. It consists of a hydraulic pump, a motor and thermos stat . It is used when accurate temperature control is needed.

Heaters: In cold regions, viscosity becomes high causing high pressure loss in the system. Hence electronic heater or steam heaters are used for heating the oil to the desired temperature.

2 Pumps

Pumps used in hydraulic systems are Positive displacement pumps.
(*Rotodynamic pumps like centrifugal pump are not used*)

Most commonly used pumps are

1. Gear Pump (External or Internal)
2. Vane Pump
3. Piston pump (Axial – Regular or Bent Axis type)

These pumps deliver a constant volume of fluid in a cycle. The discharge quantity per revolution is fixed in these pumps and they produce fluid flow proportional to their displacement and rotor speed. These pumps are used in most of the industrial fluid power applications. The output fluid flow is constant and is independent of the system pressure (load).

Points to Note about Pumps:

Positive displacement pumps

- i. generate high pressures,
- ii. high volumetric efficiency,
- iii. high power to weight ratio,
- iv. have little change in efficiency throughout the pressure range
- v. have wide operating range pressure and speed.

The fluid flow rate of these pumps ranges from 0.1 to 15,000 gpm, and the pressure ranges between 1 to 700 bar.

Pressure is a back effect: Positive displacement pumps do not produce pressure but they only produce fluid flow. The resistance to output fluid flow generates the pressure. It means that if the discharge port (output) of a positive displacement pump is opened to the atmosphere, then fluid flow will not generate any output pressure above atmospheric pressure. But, if the discharge port is partially blocked, then the pressure will rise due to the increase in fluid flow resistance. If the discharge port of the pump is completely blocked, then an infinite resistance will be generated. This will result in the breakage of the weakest component in the circuit. Therefore, a safety valves called relief valve is invariably provided in the hydraulic circuits.

2.1 Gear Pumps

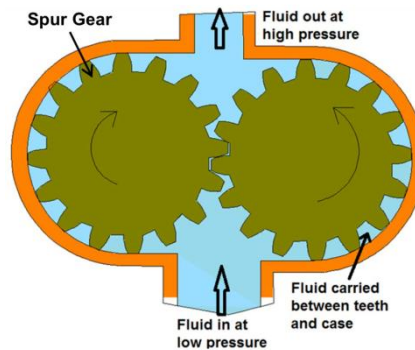
Gear pump is a robust and simple positive displacement pump. It has two meshed gears revolving about their respective axes. These gears are the only moving parts in the pump. They are compact, relatively inexpensive and have few moving parts.

Gear pumps are most commonly used for the hydraulic fluid power applications and are also widely used in chemical industries.

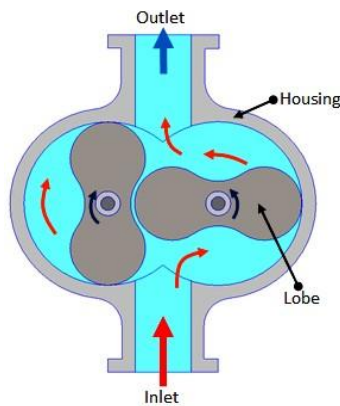
Based upon the design, the gear pumps are classified as:

- External gear pumps
- Lobe pumps
- Internal gear pumps
- Gerotor pumps

2.2 External gear pump



2.3 Lobe Pump

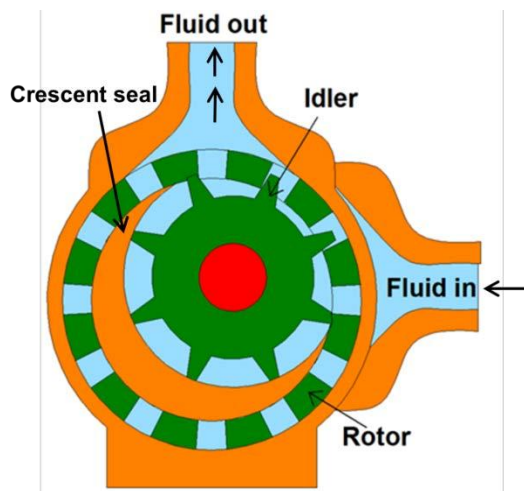


Working: One of the two gears / lobes is connected to a motor and causes rotation of the other. As they rotate in the direction shown, vacuum is created on the inlet side, liquid is trapped between the gear teeth / lobe and the motor casing. On further rotation liquid is forced to the outlet side. The gear teeth or lobes at the centre provide a seal between the inlet and outlet.

The volume displaced (d_p) is product of the area entrapped and width of tooth per each revolution and is constant. Flow rate is $N \times d_p$, where N is the speed of motor. (use appropriate units)

2.4 Internal Gear Pump:

Working : The internal gear is eccentric to the outer gear. Rotation of the internal gear causes suction on inlet side, liquid is trapped between internal gear teeth and the crescent seal, and is forced out to outlet port.

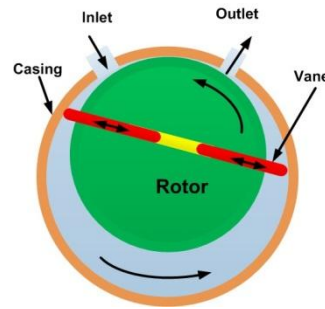


Internal gear pumps are exceptionally versatile. They are often used for low or medium viscosity fluids such as solvents and fuel oil and wide range of temperature. This is non-pulsing, self-priming and can run dry for short periods. It is a variation of the basic gear pump.

2.5 Vane Pumps

Gear pumps have a disadvantage of small leakage due to gap between gear teeth and the pump housing. This limitation is overcome in vane pumps.

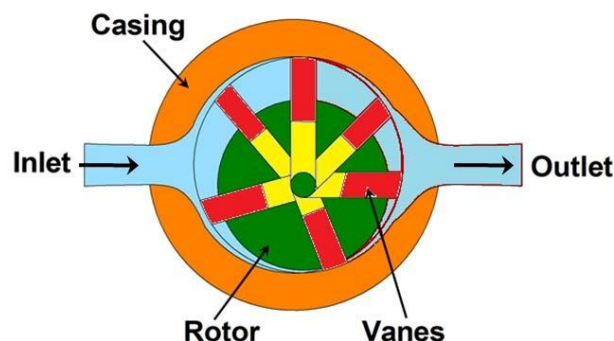
Working principle: The schematic of vane pump working principle is shown in figure. Vane pumps generate a pumping action by tracking of vanes along the casing wall.



The vane pumps generally consist of a rotor, vanes, ring and a port plate with inlet and outlet ports. The rotor in a vane pump is connected to the prime mover through a shaft. The vanes are located on the slotted rotor. The rotor is eccentrically placed inside a cam ring as shown in the figure. The rotor is sealed into the cam by two side plates. When the prime mover rotates the rotor, the *vanes are thrown outward due to centrifugal force*. The vanes track along the ring. It provides a tight hydraulic seal to the fluid which is more at the higher rotation speed due to higher centrifugal force. This produces a suction cavity in the ring as the rotor rotates. It creates vacuum at the inlet and therefore, the fluid is pushed into the pump through the inlet. The fluid is carried around to the outlet by the vanes whose retraction causes the fluid to be expelled. The capacity of the pump depends upon the eccentricity, expansion of vanes, width of vanes and speed of the rotor. It can be noted that the fluid flow will not occur when the eccentricity is zero.

2.6 Unbalanced Vane pump:

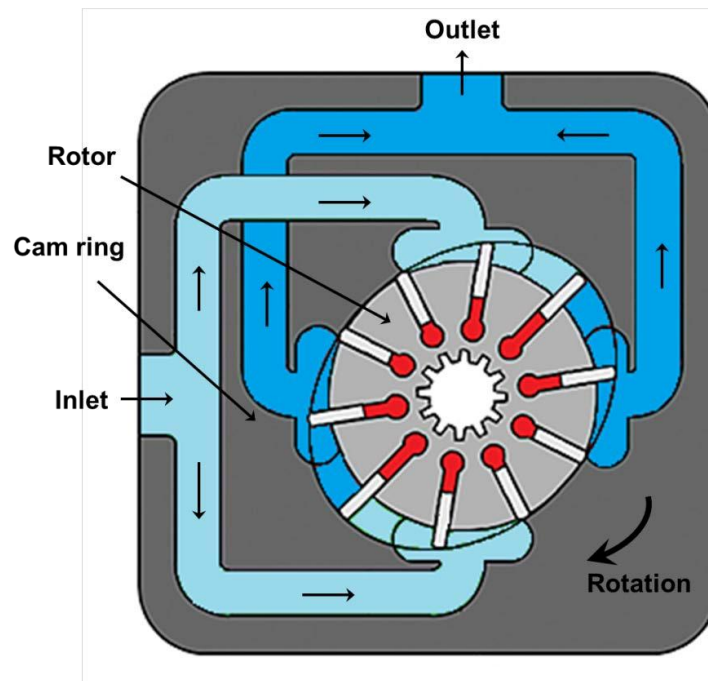
In practice, the vane pumps have more than one vane as shown in figure



The rotor is offset within the housing, and the vanes are constrained by a cam ring as they cross inlet and outlet ports. Although the vane tips are held against the housing, still a small amount of leakage exists between rotor faces and body sides. This type of pump is called as unbalanced vane pump.

2.7 Balanced vane pump

This pump has an elliptical cam ring with two inlet and two outlet ports. Pressure loading still occurs in the vanes but the two identical pump halves create equal but opposite forces on the rotor. It leads to the zero net force on the shaft and bearings. Thus, life of pump and bearing increase significantly. Also the sound and vibration are less.



Balanced Vane Pump

2.8 Axial Piston Pump

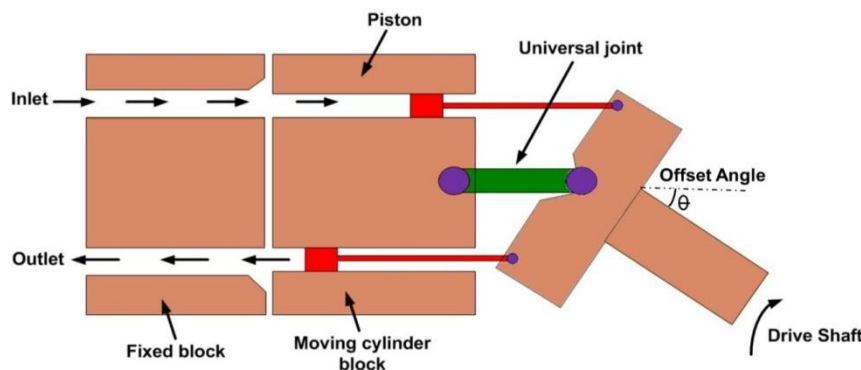
Axial piston pumps are positive displacement pumps which convert rotary motion of the input shaft into an axial reciprocating motion of the pistons. These pumps have a number of pistons (usually an odd number) in a circular array within a housing which is commonly referred to as a cylinder block, rotor or barrel. In general, these systems have a maximum operating temperature of about 120 °C. Therefore, the leakage between cylinder

housing and body block is used for cooling and lubrication of the rotating parts. This cylinder block rotates by an integral shaft aligned with the pistons. There are two types of axial piston pumps.

- a. Bent axis piston pumps
- b. Swash plate axial piston pump

2.9.a Bent-Axis Piston Pump

In these pumps, the reciprocating action of the pistons is obtained by bending the axis of the cylinder block. The cylinder block rotates at an angle which is inclined to the drive shaft. The cylinder block is turned by the drive shaft through a universal link. The cylinder block is set at an offset angle with the drive shaft. The cylinder block contains a number of pistons along its periphery. These piston rods are connected with the drive shaft flange by ball-and-socket joints. These pistons are forced in and out of their bores as the distance between the drive shaft flange and the cylinder block changes. A universal link connects the block to the drive shaft, to provide alignment and a positive drive.



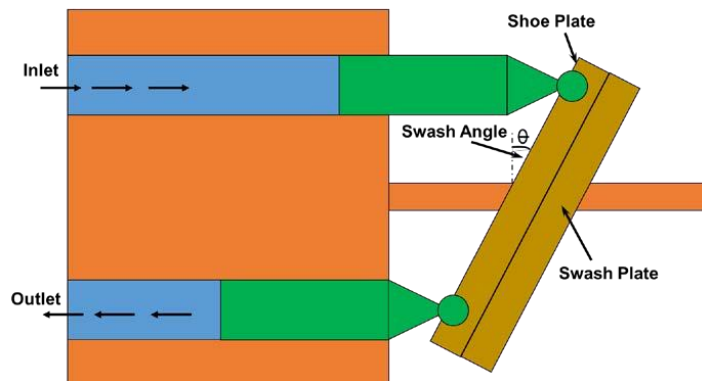
Bent Axis Piston pump

The volumetric displacement (discharge) of the pump is controlled by changing the offset angle.

2.9.b Swash Plate Axial Piston Pump

A swash plate is a device that translates the rotary motion of a shaft into the reciprocating motion. It consists of a disk attached to a shaft as shown in Figure. If the disk is aligned perpendicular to the shaft; the disk will turn along with the rotating shaft without any reciprocating effect. Similarly, the edge of the inclined shaft will appear to oscillate along the shaft's length. This apparent linear motion increases with increase in the angle between disk and the shaft (offset angle).

The apparent linear motion can be converted into an actual reciprocating motion by means of a follower that does not turn with the swash plate.



Swash plate piston pump

In swash plate axial piston pump a series of pistons are aligned coaxially with a shaft through a swash plate to pump a fluid. The axial reciprocating motion of pistons is obtained by a swash plate that is either fixed or has variable degree of angle. *As the piston barrel assembly rotates, the piston rotates around the shaft with the piston shoes in contact with the swash plate.* The piston shoes follow the angled surface of the swash plate and the rotational motion of the shaft is converted into the reciprocating motion of the pistons. Pump capacity can be controlled by varying the swash plate angle with the help of a separate hydraulic cylinder.

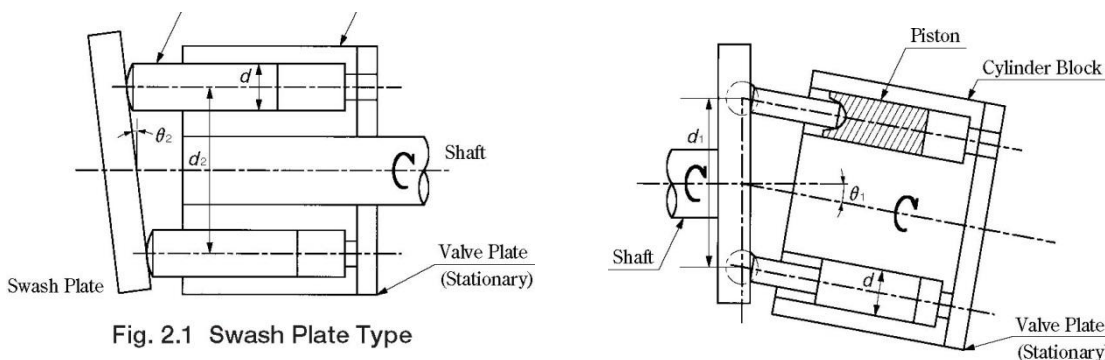


Fig. 2.1 Swash Plate Type

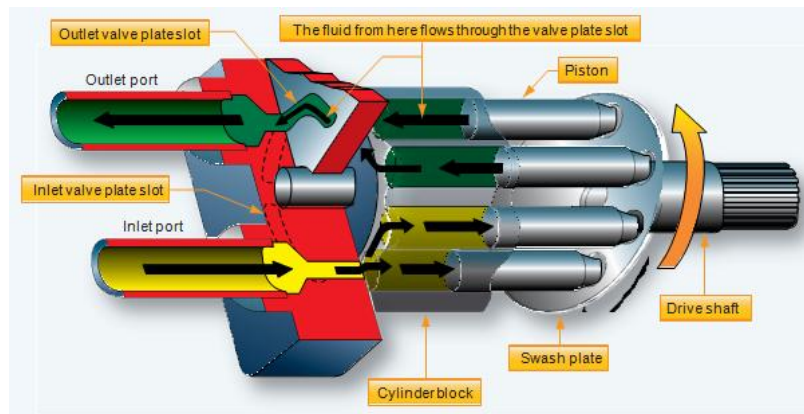
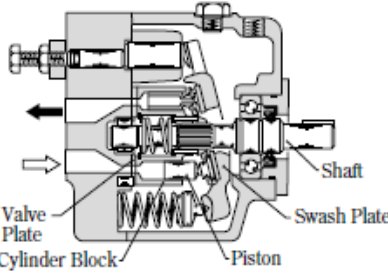
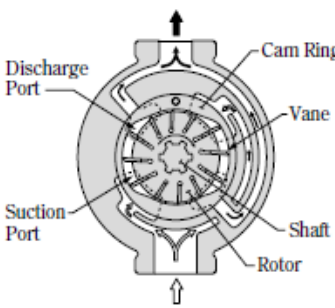
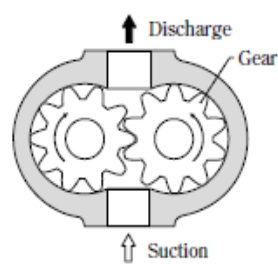


Table 2.1 Characteristics of the Pumps

Type	Piston Pumps	Vane Pumps	Gear Pumps
Structure			
Operation Principle	Expansion and compression of a volume in a cylinder block with the piston stroke	Expansion and compression of volumes between the vanes and the cam ring	Movement of volumes between tooth spaces and the casing (the external gear pump is shown.)
Efficiency	<ul style="list-style-type: none"> • Generally the highest. • The valve plate is easily damaged and efficiency drops as the plate wears out. 	<ul style="list-style-type: none"> • Generally low. • Can be compensated when the vane wears out. 	<ul style="list-style-type: none"> • Generally low. • Drops as the gear wears out.
Contamination Resistance	Highly susceptible to foreign substances in oil.	Susceptible to foreign substances in oil, but less so than piston pumps.	Susceptible to foreign substances in oil, but hardly susceptible when the pumps are low pressure types.
Suction Ability	Low.	Middle.	High.
Variable Displacement Type	Easy to convert by changing the angle of the swash plate or bent axis.	Can be converted by changing the eccentricity of the cam ring for the unbalanced type.	Difficult.
Size and price	Generally large, heavy, and expensive.	Smallest and relatively inexpensive.	Small, light, and inexpensive.

3 DIRECTIONAL CONTROL VALVES (DCV)

3.1 Directional control valves can be classified in a number of ways:

1. According to type of construction :

- Poppet valves
- Spool valves

2. According to number of working ports :

- Two- way valves
- Three – way valves
- Four- way valves.

3. According to number of Switching position:

- Two – position
- Three - position

4. According to Actuating mechanism:

- Manual actuation
- Mechanical actuation
- Solenoid (Electrical) actuation
- Hydraulic (Pilot) actuation
- Pneumatic actuation
- Indirect actuation

The designation of the directional control valve refers to the number of working ports and the number of switching positions.

3.2 How to read the valve schematic:

Symbols: P – Pressure port (high pressure oil inlet from pump)

T – Tank or return port connected to tank

A, B – Ports connected to actuator (eg., piston side and rod side of cylinder)

The figure below represents a 2 position, 4-way (or 4- port) valve .

The two rectangular blocks represent two positions of possible actuation of valve. A, B, P and T are the 4 ports of the valve connected to different components. Hence it is called a 2/4 valve.

The construction or design of the valve is such that when valve is actuated to left side, as shown by arrows, pressure line from pump is connected to A side of actuator, and B side is connected to the tank.

Similarly when valve is switched to second position, the right side is effective. (Now read the four symbols A, B, P, T on the four ports in right rectangle, which is effective). From the arrows it means P is connected to B and A is connected to T).

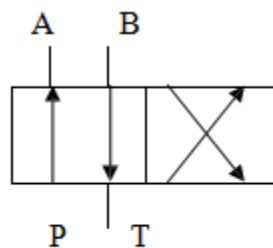
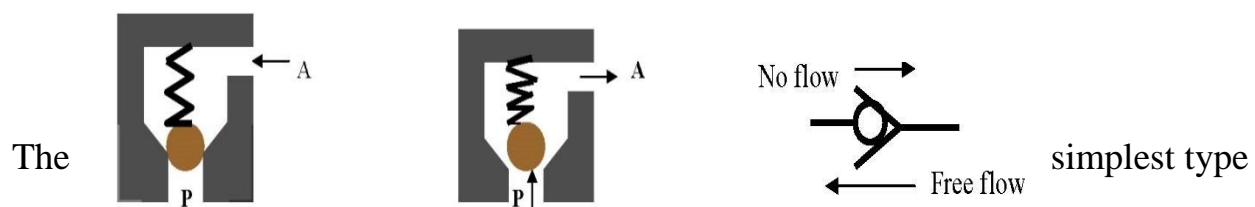


Fig 4.3. 2/4 valve symbol

1. **Check Valve:** This valve allows flow from P to A ., when pressure is enough to overcome the spring force acting on the ball, which is quite small. It does not allow flow in the other direction ie from A to P .

The symbol for check valve is as shown. It is also called On-off or Non-return valve.



of directional control valve is a check valve which is a two way valve because it contains two ports. These valves are also called as on-off valves because they allow the fluid flow in only in one direction and the valve is normally closed. Two – way valves is usually the spool or poppet design with the poppet

2. Spool type on/ off valve: As can be seen from the figure,

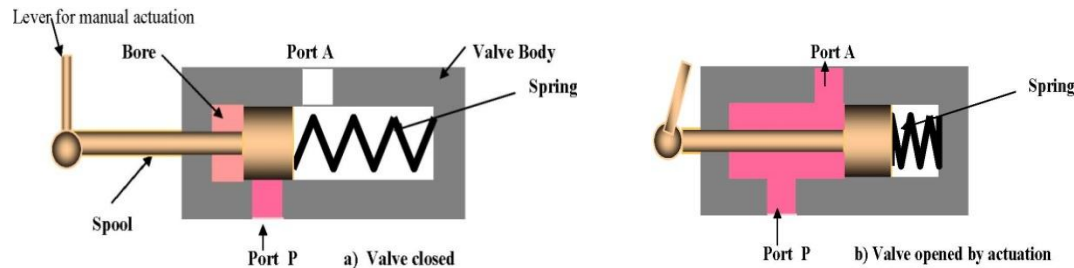
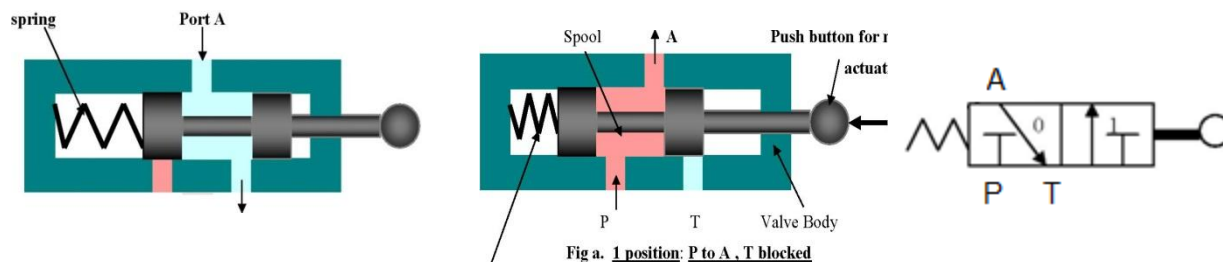


Fig 4.7 Spool type 2/2 DCV

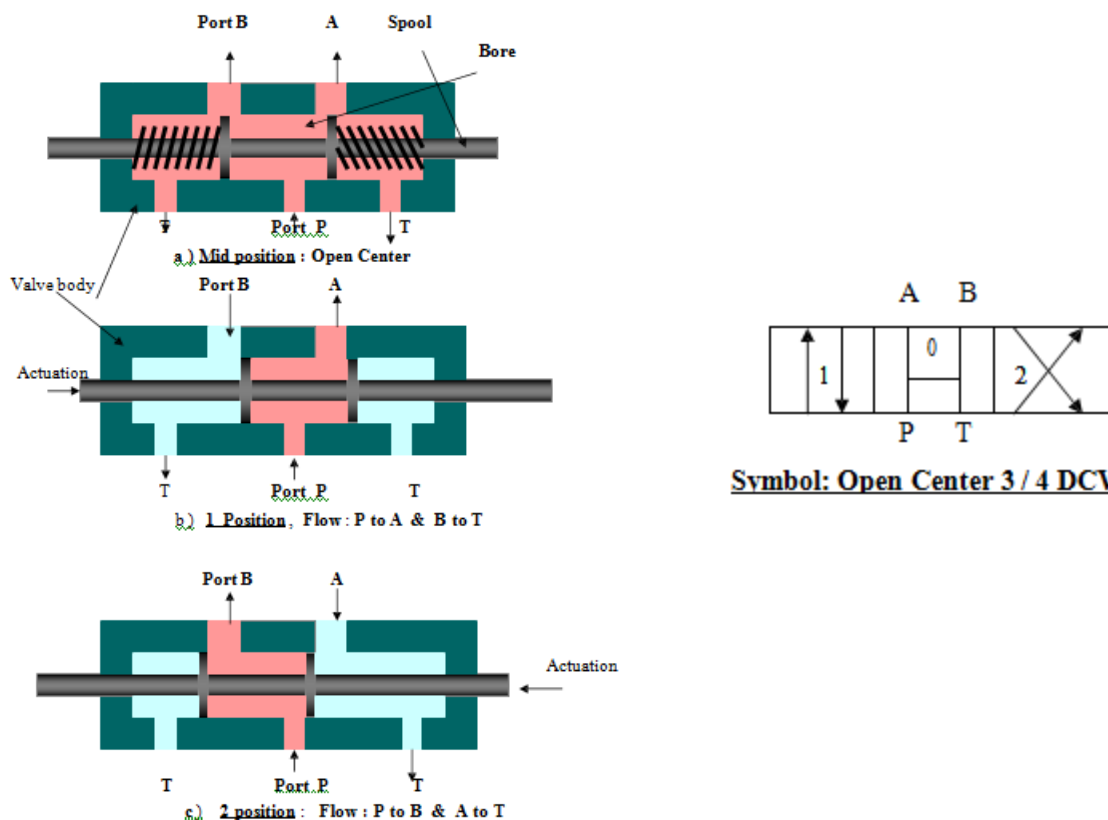
3. 2-position, 3-way valve



Symbol of 2/3 valve

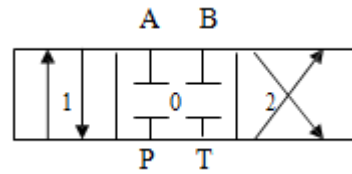
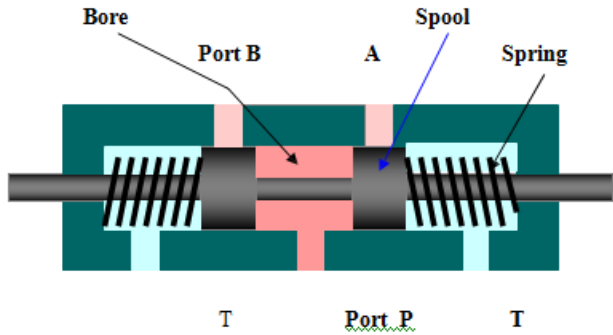
Position 0: A to T
Position 1: P to A

4. Open center 3/4 DCV



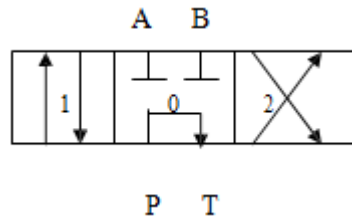
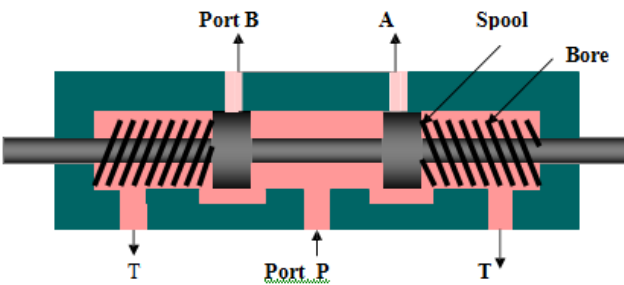
Symbol: Open Center 3/4 DCV

5. Closed Center 3 / 4 DCV:



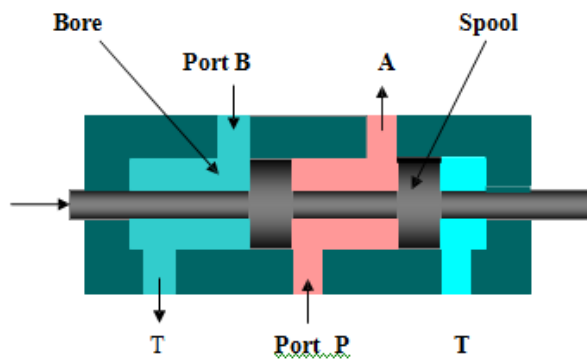
Mid Position: Closed Center 3 / 4 DCV

6. Tandem centered 3 / 4 DCV

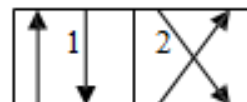
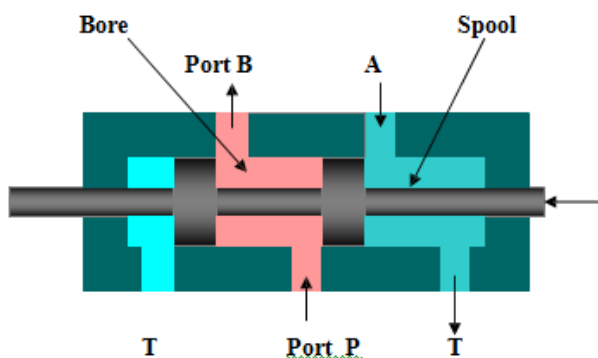


Tandem Center 3 / 4 DCV : Mid position

7. Two position, Four – way DCV :



a. 1 Position : P to A and B to T



3.3 Actuation of Directional control valves: Directional control valves can be actuated by different methods.

Manually – actuated Valve: A manually actuated DCV uses muscle power to actuate the spool. Manual actuators are hand lever, push button, pedals . The following symbols show the DCV actuated manually

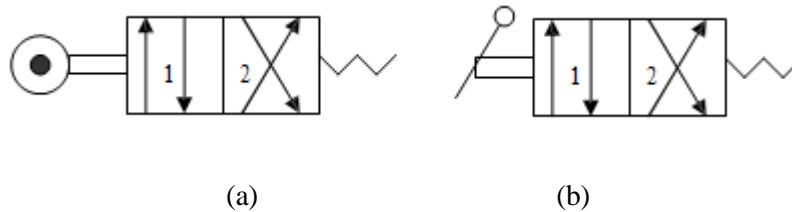
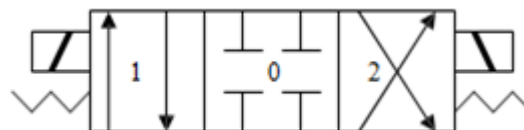
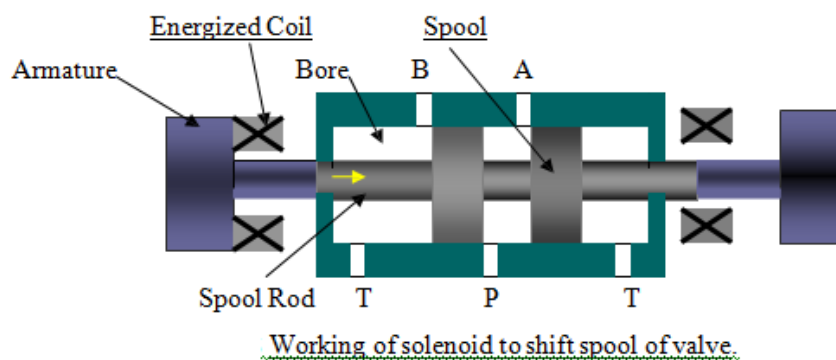


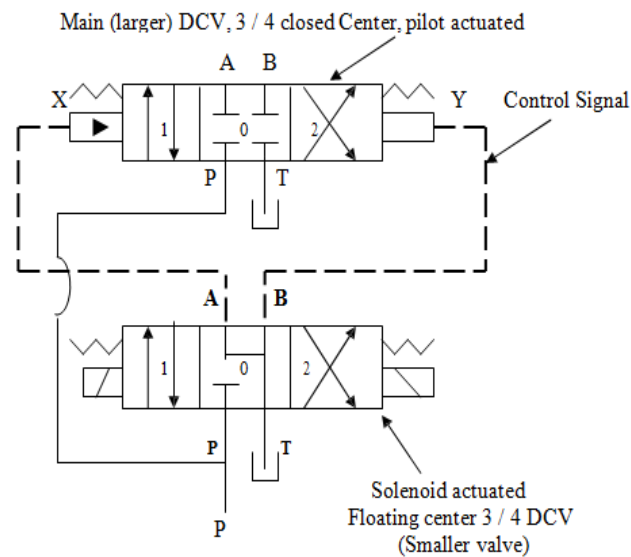
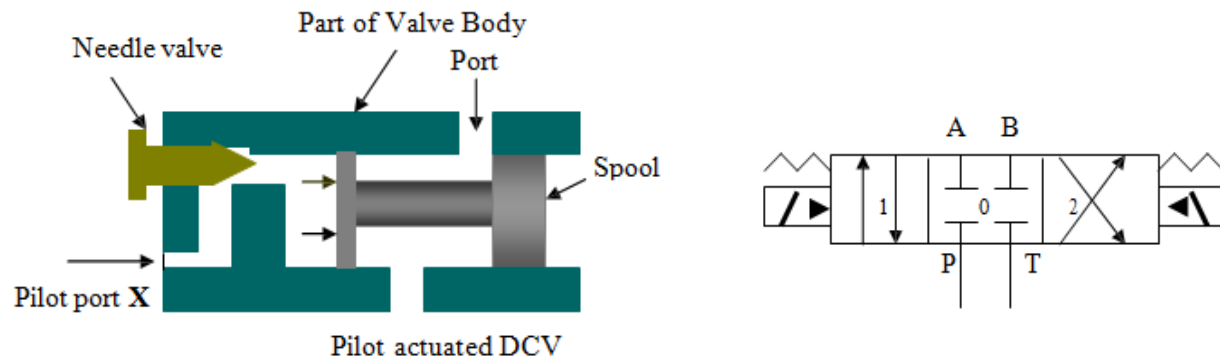
Fig a & b shows the symbol of 2 / 4 DCV manually operated by hand lever to 1 and spring return to 2. In the above two symbols the DCV spool is returned by springs which push the spool back to its initial position once the operating force has stopped.

Mechanical Actuation: The DCV spool can be actuated mechanically, by roller and cam, roller and plunger. The spool end contains the roller and the plunger or cam can be attached to the actuator (cylinder).. When the cylinder reaches a specific position the DCV is actuated. The roller tappet connected to the spool is pushed in by a cam or plunger and presses on the spool to shift it either to right or left reversing the direction of flow to the cylinder. A spring is often used to bring the valve to its center configuration when deactivated.

Solenoid Actuated DCV: A very common way to actuate a spool valve is by using a solenoid is illustrated in the figure. When the electric coil (solenoid) is energized, it creates a magnetic force that pulls the armature into the coil. This caused the armature to push on the spool rod to move the spool of the valve.. The advantage of a solenoid valve is that the switching time is less.



Hydraulic actuation: This type actuation is usually known as pilot-actuated valve. The hydraulic pressure may be directly used on the end face of the spool. The pilot ports are located on the valve ends. Figure shows a DCV where the rate of shifting the spool from one side to another can be controlled by a needle valve. Fluid entering the pilot pressure port on the X end flows through the check valve and operates against the piston. This forces the spool to move towards the opposite position. Fluid in the Y end (right end, not shown in the figure) is passed through the adjustable needle valve and exhausted back to tank. The amount of fluid bled through the needle valve controls how fast the valve will shift.

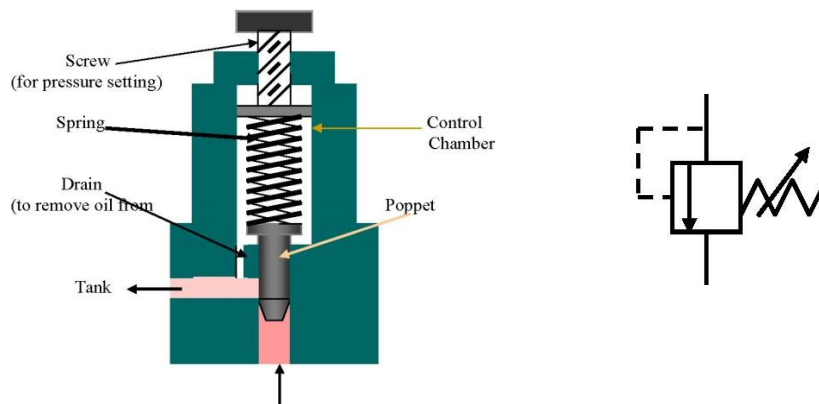


Indirect actuation of directional control valve

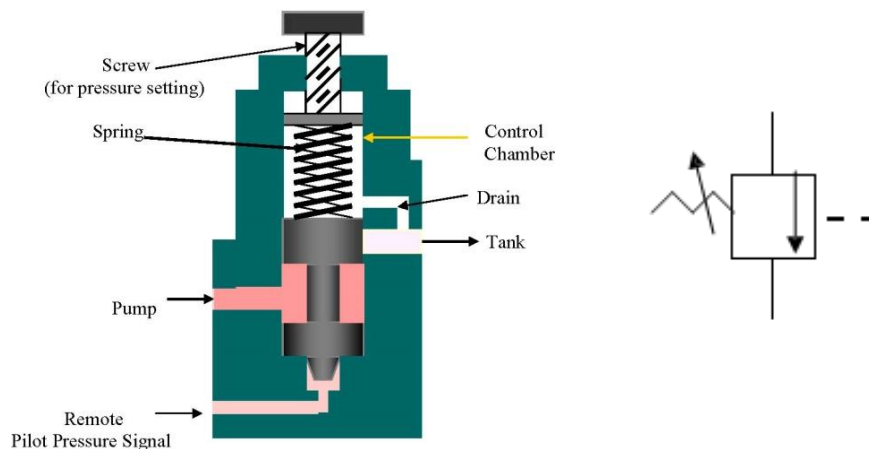
4 Pressure Relief Valves

The pressure relief valve is used to protect the hydraulic components from excessive pressure. It is one of the most important components of a hydraulic system and is essentially required for safe operation of the system. Its primary function is to limit the system pressure within a specified range. It is normally a closed type and it opens when the pressure exceeds a specified maximum value by diverting pump flow back to the tank. The simplest type valve contains a poppet held in a seat against the spring force as shown in the figure. The fluid enters from the opposite side of the poppet. When the system pressure exceeds the preset value, the poppet lifts and the fluid is escaped through the orifice to the storage tank directly. It reduces the system pressure and as the pressure reduces to the set limit again the valve closes. This valve does not provide a flat cut-off pressure limit with flow rate because the spring must be deflected more when the flow rate is higher. Various types of pressure control valves are discussed in the following sections:

1. Pressure Relief Valve: When the system pressure exceeds a set value, the poppet raises up and allows fluid to flow back to tank.

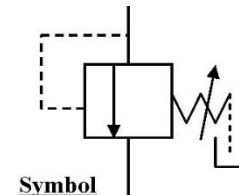
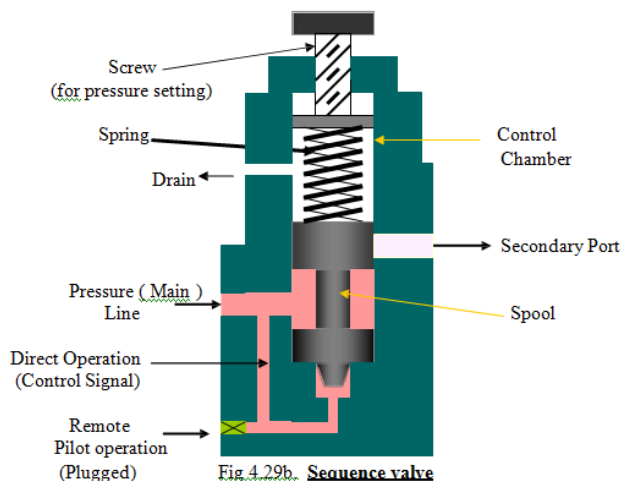


2. Unloading Valve: A unloading valve is used to permit a pump to operate at minimum load. The unloading valve is normally closed valve with the spool closing the tank port. When a pilot pressure is enough to overcome the spring force, spool moves up and flow is diverted to tank. When the pilot pressure is relaxed, spool moves down and lets the flow to the circuit for operation.

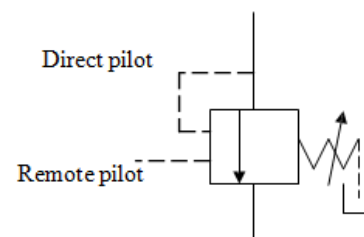
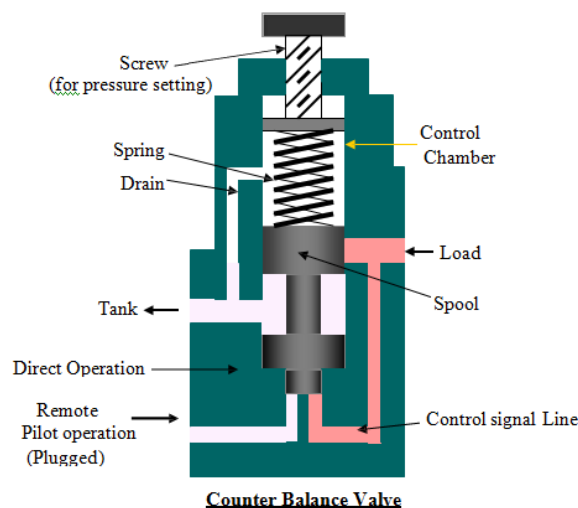


The unloading valve is used in system having one or more fixed delivery pump to control the amount of flow at any given time. A well designed hydraulic circuit uses the correct amount of fluid for each phase of a given cycle of machine operations. When pressure builds up during the feed phase of the cycle, the pilot pressure opens the unloading valve, causing the large discharge pump to bypass its flow back to the tank.

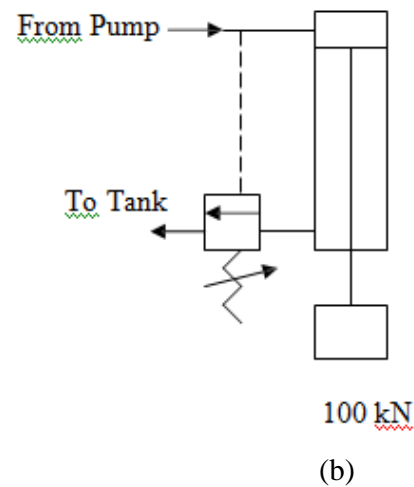
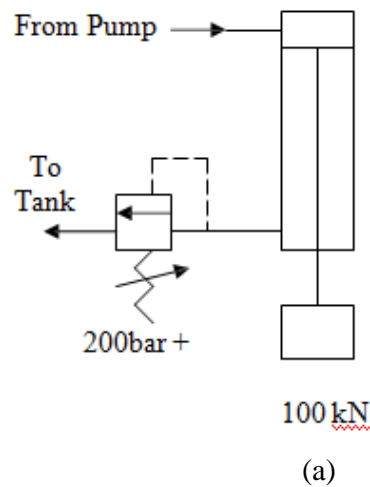
3. **Sequence valve:** A sequence valve's primary function is to divert flow in a predetermined sequence. It is a pressure-actuated valve similar in construction to a relief valve and normally a closed valve. When the main system pressure overcomes the spring setting, the valve spool moves up allowing flow from the secondary port.



4. **Counter balance Valve:** A Counter balance valve is used to maintain back pressure to prevent a load from falling. One can find application in vertical presses, lift trucks, loaders and other machine tool that must position or hold suspended loads.

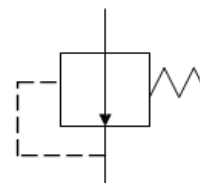
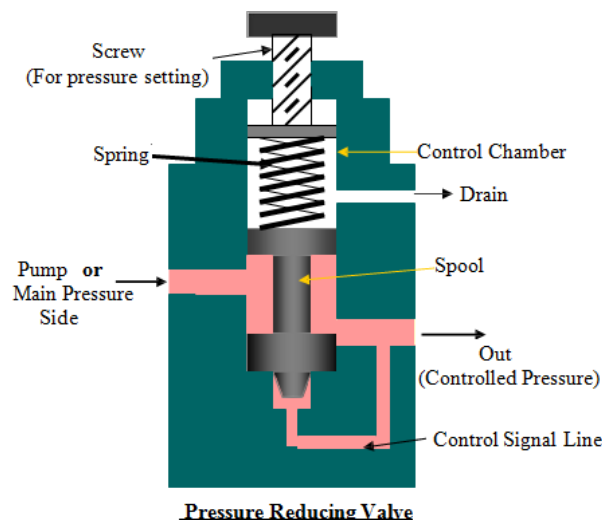


When a counterbalance valve is used on large vertical presses, it may be important to analyze the source of pilot pressure. Figures (a) and (b) illustrate the comparison between direct and remote pilot signal



5. Pressure Reducing Valve: Pressure reducing valve is used to limit its outlet pressure. Reducing valves are used for the operation of branch circuits, where pressure may be less than the main system pressure.

The pressure reducing valve is normally an open type valve. When the secondary pressure is high, it lifts the spool against the spring force and throttles the flow till such extent that the secondary pressure reaches the value as set by spring.



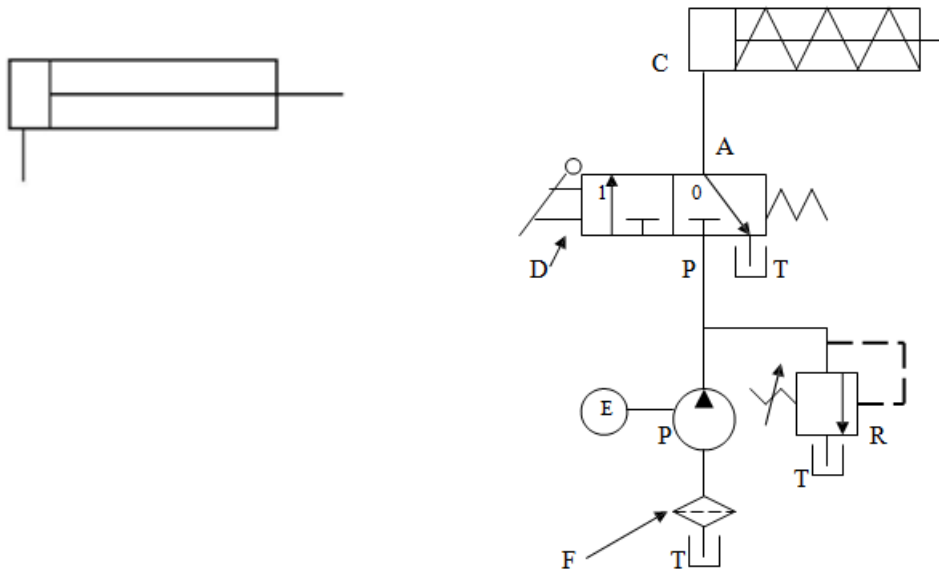
5. SOME TYPICAL HYDRAULIC CIRCUITS

5.1 In this part we will look at some of the simple and commonly encountered hydraulic circuits. The circuits are drawn using the standard graphical symbols.

1. Control of a Single- Acting Hydraulic Cylinder

In single acting cylinder hydraulic force is exerted on the piston for forward movement (to right in the figure shown). For retraction, no hydraulic force is applied and the rod moves (to left) due to a spring force or weight of the piston and rod

Figure shows a two-position, three way, manually operated, spring offset directional control valve (DCV) used to control the operation of a single – acting cylinder.

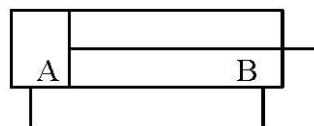


As valve is moved to occupy position 1 (left) flow goes to rod end and rod is pushed to right.

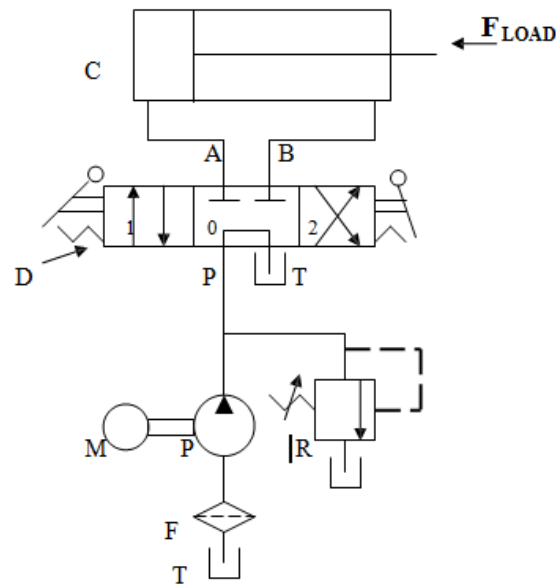
When valve is moved to position 0, i.e. shifted to right indicated position, flow from pump is blocked in the valve. There is no hydraulic pressure on the piston side. The flow goes to tank via relief valve at the set pressure. The actuator moves to left due to spring force acting on the rod end of piston.

2. Control of Double Acting Hydraulic Cylinder:

Double –Acting cylinders can be extended and retracted hydraulically. Thus, an output force can be applied in two directions.



Double acting cylinder



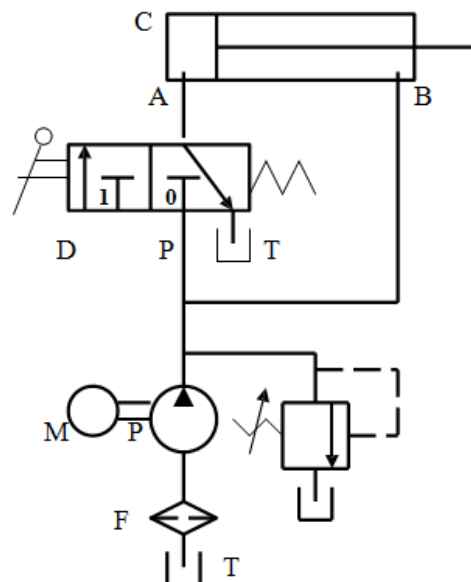
The valve is manual 3position /4-way valve. In the neutral or valve central (0) position, oil from pump goes to tank, and no action on actuator. Note that the valve does not go through relief valve to tank, thereby saving power (Pressure set in relief valve x pump flow rate). There is minor power loss due to drop in valve orifices, and piping.

In position 1 of valve, oil flow is P to A. ie. from pump to piston side and rod moves to right acting on the load. Oil from rod side chamber of cylinder goes to tank (B to T).

In position 2, Oil from pump goes to rod end (P to B) and Oil from piston end goes to tank. (A to T) thereby pushing the rod (load) to left.

3. Regenerative circuit:

Operation: Figure shows a regenerative circuit that is used to speed up the extending speed of a double-acting hydraulic cylinder.



It can be seen that in position 1 when pump is connected to piston side chamber ,ie., when main load is operated, fluid from piston side also flows into it. Thereby the flow rate is more than

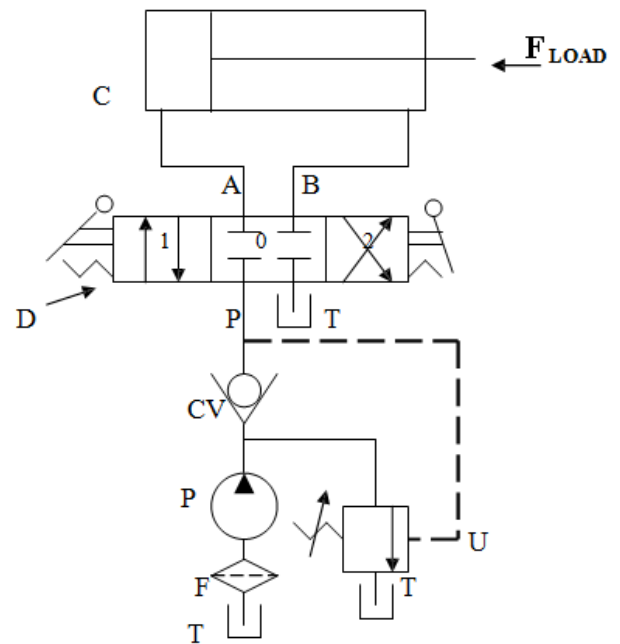
pump flow. Thus the velocity of actuation on piston side is increased by the ratio (A_p / A_r), where A_p is the piston area and A_r is the rod area. .

However, the net force due to the piston rod is reduced to $A_r \times \text{Pressure}$.

In position 2, when flow is directed to rod side, oil from the piston side flows to tank directly.

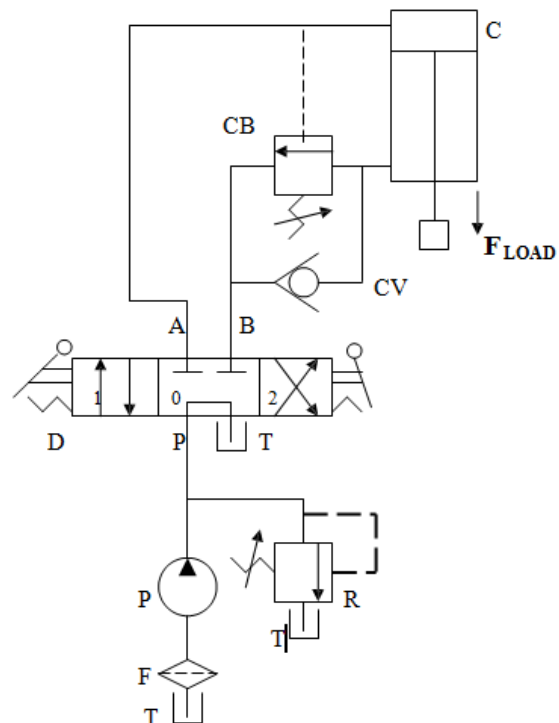
4. Pump Unloading Circuit

The figure shows a circuit using an unloading valve to unload a pump. The unloading valve opens when the cylinder reaches the end of its extension stroke because the check valve keeps high-pressure oil in the pilot line of the unloading valve. When the DCV is shifted to retract the cylinder, the motion of the piston reduces the pressure in the pilot line of the unloading valve. This resets the unloading valve until the cylinder is fully retracted, at which point the unloading valve unloads the pump. Thus, the unloading valve unloads the pump at the ends of the extending and retraction strokes as well as in the spring-centered position of the DCV.



5. Counter Balance Valve Application

Counter balance valve is used to hold loads in vertical position without descending while idling in neutral position. Rod side fluid cannot flow unless a pilot pressure acts on the valve and permits flow to tank. The valve spring so set that pressure required is higher than for upward stroke.



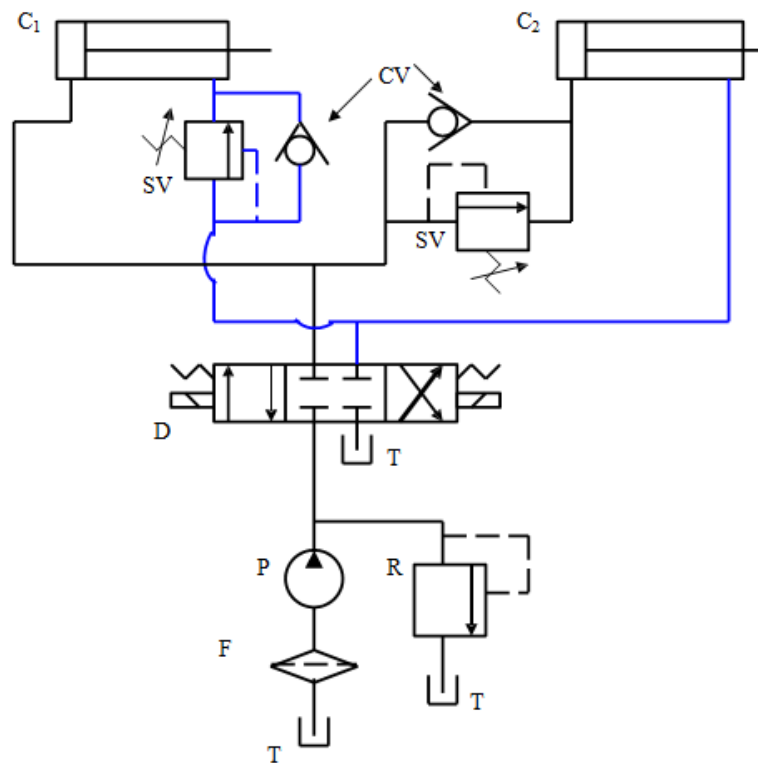
5.2 Hydraulic Cylinder Sequencing Circuits:

Figure shows an example where two sequence valves are used to control the sequence of operations of two double-acting cylinders C1 and C2. When the DCV is shifted into its left position, the left cylinder extends completely, and pressure builds up and only when the left cylinder pressure reaches the pressure setting of sequence valve, the sequence valve connected to the right cylinder opens and permits flow to rod end of C2, and extends it.

If the DCV is then shifted to right position, flow to rod end of C1 is blocked, but flows freely to rod end of C2. After C2 retracts fully, pressure builds up till the valve connected to C1 opens.

Thus the sequence is C1Ext - C2Ext - C2Retr - C1 Retr.

One can find the application of this circuit in press circuit. For example, the left cylinder the clamping cylinder C1 could extend and clamp a workpiece. Then the right cylinder C2, the punching cylinder extends to punch a hole in the workpiece. The right cylinder then retracts the punch, and then the left cylinder retracts to declamp the workpiece for removal.

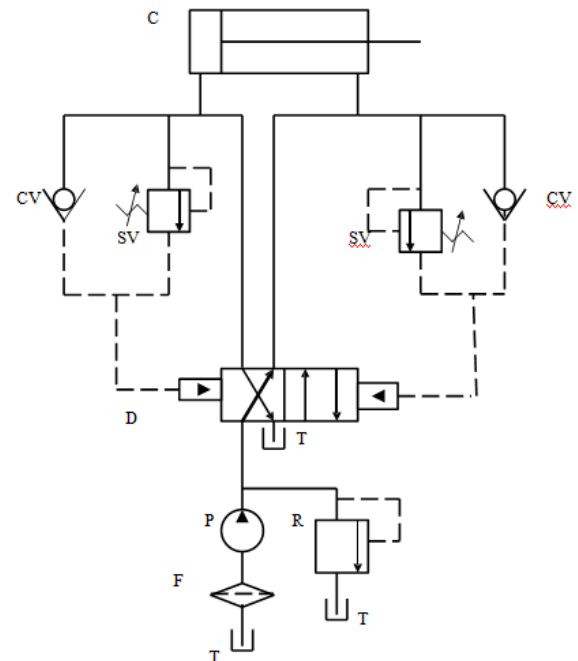


Cylinder Sequencing circuit

5.3 Automatic Cylinder Reciprocating System –

(i) Using Sequence Valves

Operation: In the left position of valve shown, P is connected to rod-side, and the rod retracts. After piston reaches the left end, pressure builds up on rod side which opens the sequence valve on the right and permits pilot hydraulic line to act on the main DCV to switch to right position. Check valves allow pilot oil to leave either end of the DCV while pilot pressure is applied to the opposite end.



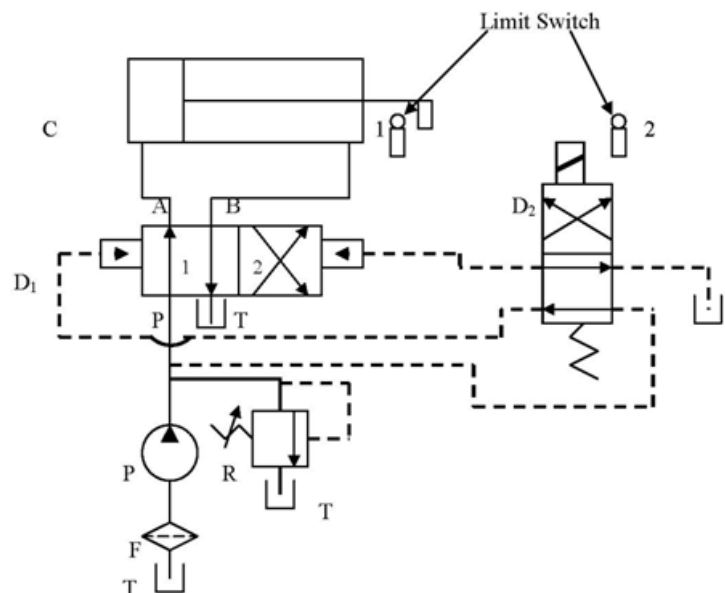
Automatic Cylinder Reciprocating System using Sequence valves

(ii) An alternative circuit is shown using limit switches and solenoid valve, and a pilot operated DCV. .

Operation: Suppose the left position of the main DCV is on.

Then the piston rod moves to right > It hits the limit switch 2 > which energises solenoid valve D2 > which shifts the solenoid operated DCV (D2) to position (top as shown) > which now permits pilot oil from D2 to right end of DCV D1 > changes D1 position 2 > flow is now to rod end > rod moves to left till it hits limit switch 1.

Now the reverse of the above sequence is repeated so that Position 1 of the main DCV becomes operative. Thus it leads to automatic reciprocation of the actuator between the limit switch positions.



Automatic Cylinder Reciprocating System using DCV's.

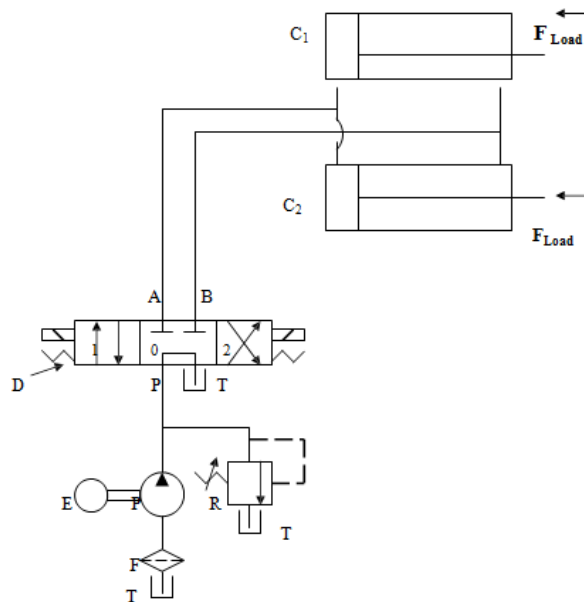
5.4 Cylinder Synchronizing Circuits :

Circuits are shown for synchronising the operation of two cylinders (ie simultaneous equal movement).

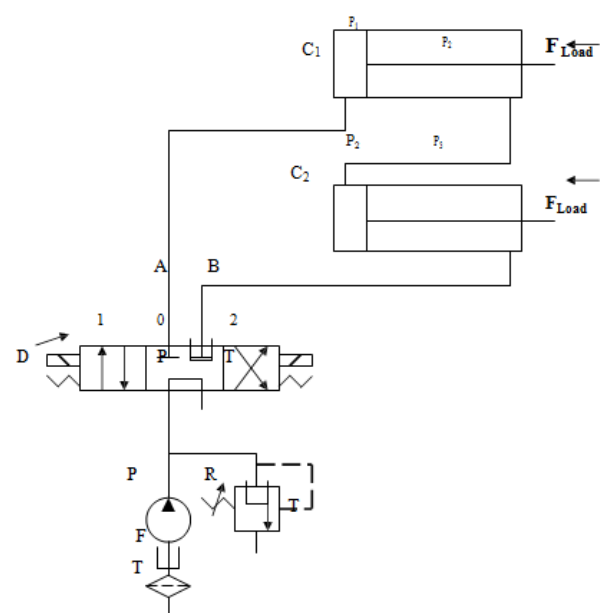
a. Cylinder connected in Parallel

In the circuit shown, piston or rod ends of both cylinders are connected to one line. Thus oil flows simultaneously. However, if load on one cylinder is more, the other cylinder needing less pressure operates first, and after completion of stroke, pressure builds up to operate the second cylinder. This operation is not synchronised. The problem may arise with slight differences in the size of cylinders as well.

- b. **Cylinders connected in Series:** The rod end of C1 is connected to piston end of C2. Thus C1 and C2 have to move together. However, for to have equal stroke, rod end area of C1 should be equal to piston area of C2. Also, rod end of C2 has to have high pressure to do work by C2. Hence piston side pressure would be that much higher.



Cylinder hooked in parallel for synchronizing
(will not operate)



Cylinder hooked in Series for synchronizing
(Will Operate.)

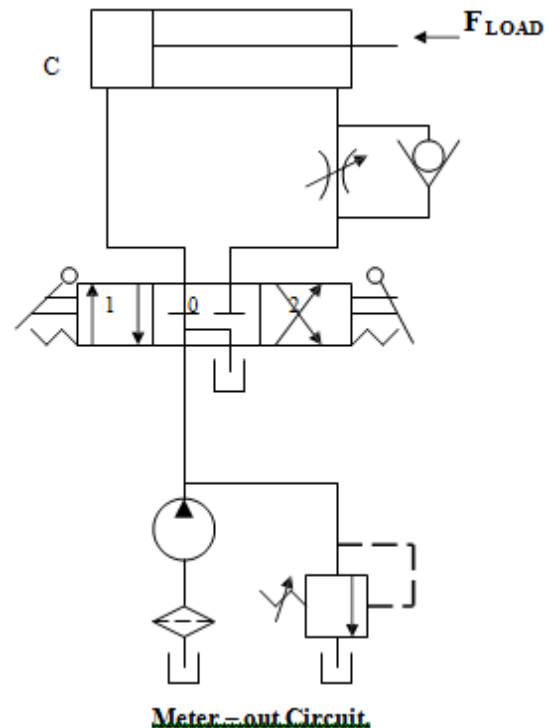
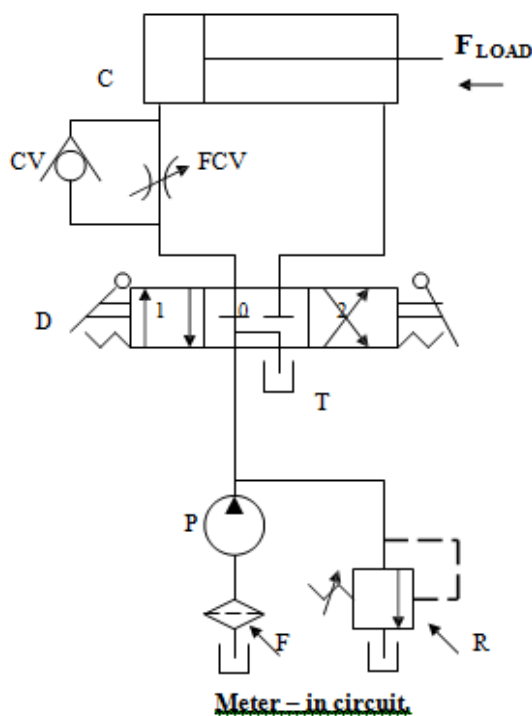
5.5 Speed Control

Speed control of Hydraulic Cylinder: Speed control of a hydraulic cylinder is accomplished using a flow control valve. A flow control valve regulates the speed of the cylinder by controlling the flow rate to and of the actuator.

There are 3 types of speed control:

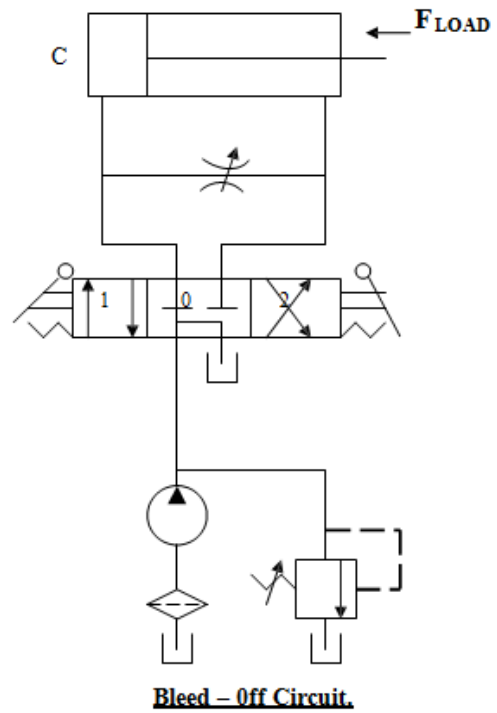
- Meter-in circuit (Primary control)
- Meter-out circuit (Secondary control)
- Bleed -off circuit (By pass control)

1. **Meter – in Circuit** : In this type of speed control, the flow control valve is placed between the pump and the actuator. Thereby, it controls the amount of fluid going into the actuator. Figure below shows meter-in circuit. When the direction is reversed, oil from piston side flows to tank via check valve as well as FC valve freely. The excess flow is dumped to tank via relief valve.



2. **Meter – out Circuit** : In this type of speed control, the flow control valve is placed between the actuator and the tank . Thereby, it controls the amount of fluid going out of the actuator and thereby the speed of retraction. Meter out circuits are useful to control free fall of loads due to gravity etc. connected to the load. Oil is dumped at load pressure but not at relief valve set pressure. However, meter –out can lead to high pressure intensification sometimes twice supply pressure, leading to damage of seals etc. Still it is favoured in drilling, reaming and milling when it is required to control the tool feed rate.

3. Bleed off circuit: This circuit is used to overcome the disadvantages of meter-in and meter-out circuits. Here, a flow control valve is kept between either ends. Flow is controlled in each direction, and excess flow to tank is not through relief valve.



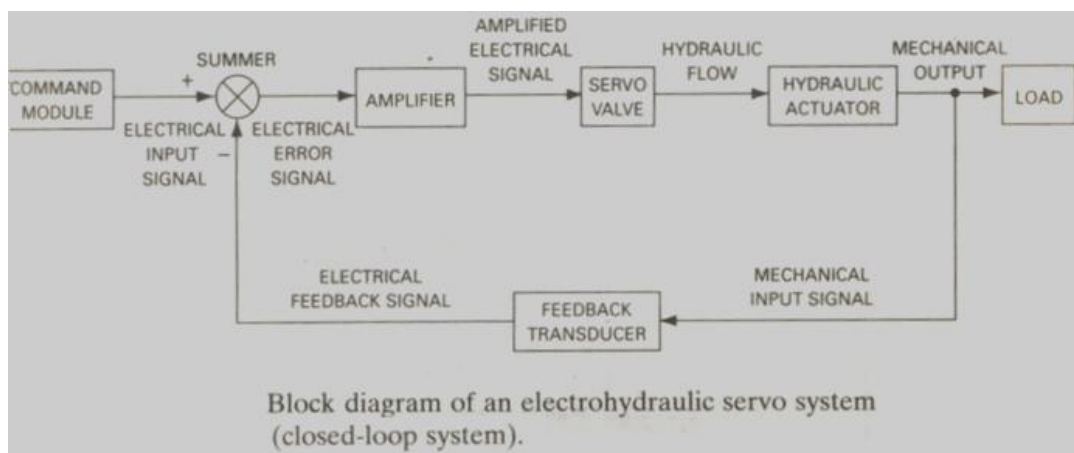
6. Hydraulic Servo Systems:

Servo systems refer to systems where automatic control of actuator movements is required. These movements should be as per a predetermined rate and deviations should be reduced to a minimum.

A servomechanism is an automatic control system designed to operate in accordance with input control parameters. The mechanism continuously compares the input signal to the feedback signal to adjust the operating conditions to correct error.

Applications: Hydraulic servo systems are widely used in the airline, maritime, and military applications. Servo systems capable of automatic position, speed, force control with high accuracy are used in high-speed injection moulding, die casting, rolling mills, presses, industrial robots, flight simulators testing machinery and table feeders.

For achieving automation, a **feedback signal**, using a **sensor**, from the actuator or any variable to be controlled such as actuator force or velocity or displacement or angle of rotation of a rotary actuator is required. This feedback signal is compared with the reference input and a suitably modified signal is sent to the flow control valve to thereby control the required variable. A block diagram representation of a hydraulic servo system is shown below.



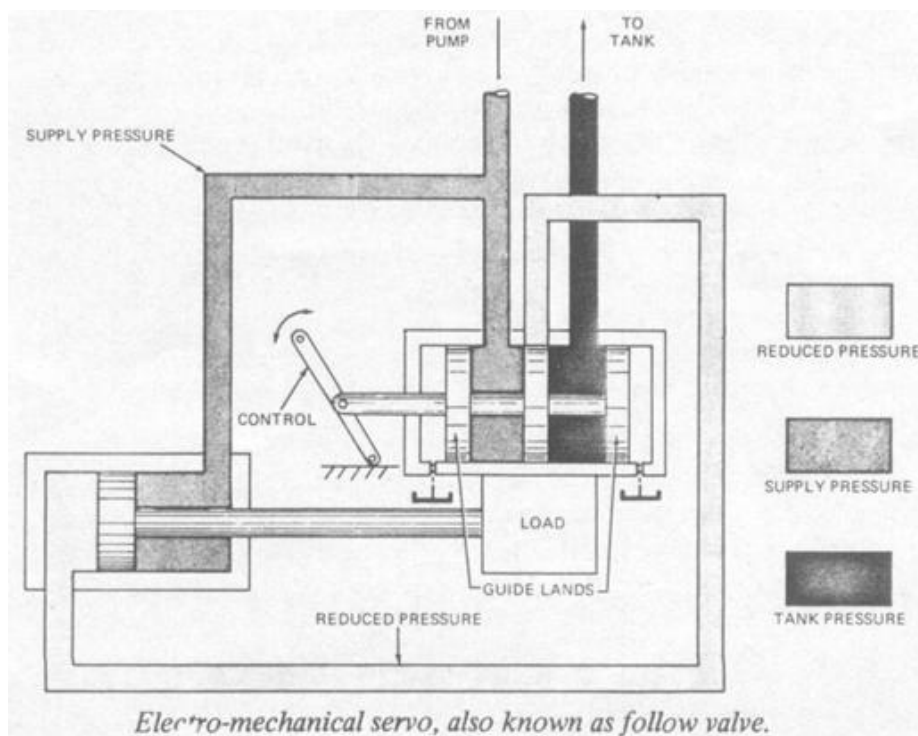
6.1 A Mechanical servo system:

In this system shown in the figure, load is connected to the valve spool, and special sensors and electrical components are not required.

Operation:

1. Input movement to the valve opens the spool (to left) for certain flow rate.
2. The flow actuates the piston and the load to left.
3. The load, being connected to the valve body, also moves to left, while the spool is in the same position.
4. Thus the opening of spool is gradually reduced as the piston moves. When the piston moves by the distance of initial spool movement, spool closes the port opening and flow becomes zero.
5. Thus Input movement of spool is related to the load movement.
6. Thus this arrangement provides a feed back signal.

A separate link can be connected to valve spool, cylinder rod and the input, to achieve a ratio of output/ input other than 1.



6.2 Proportional type valves:

Valves explained so far are on-off type, ie, they take distinctly one of the two or three positions letting full flow in either direction or stop the flow. However for servo systems valves which operate in an analog fashion, ie continuously variable control are required.

Special valves:

In view of the continuous control, special proportional control valves are used which produce movement of the spool proportional to an electrical signal. The signal given to the valve is the error signal (difference between the reference input and that sensed by the actuator), so that the system corrects to make the error zero, or actuator achieves the desired parameter.

6.2.1 Electrohydraulic Servo System:

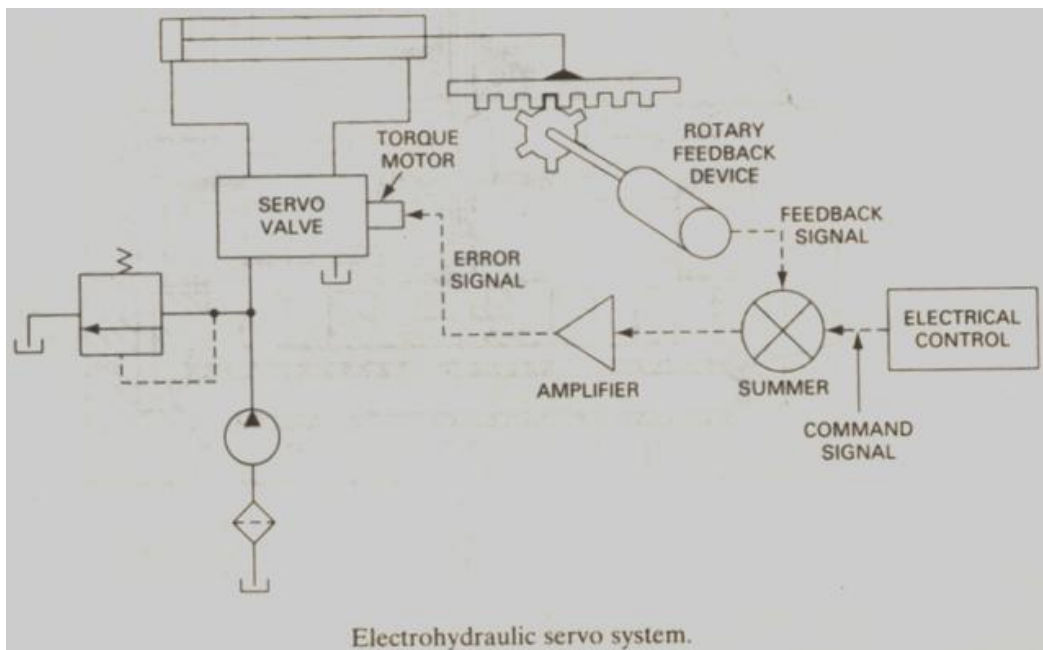
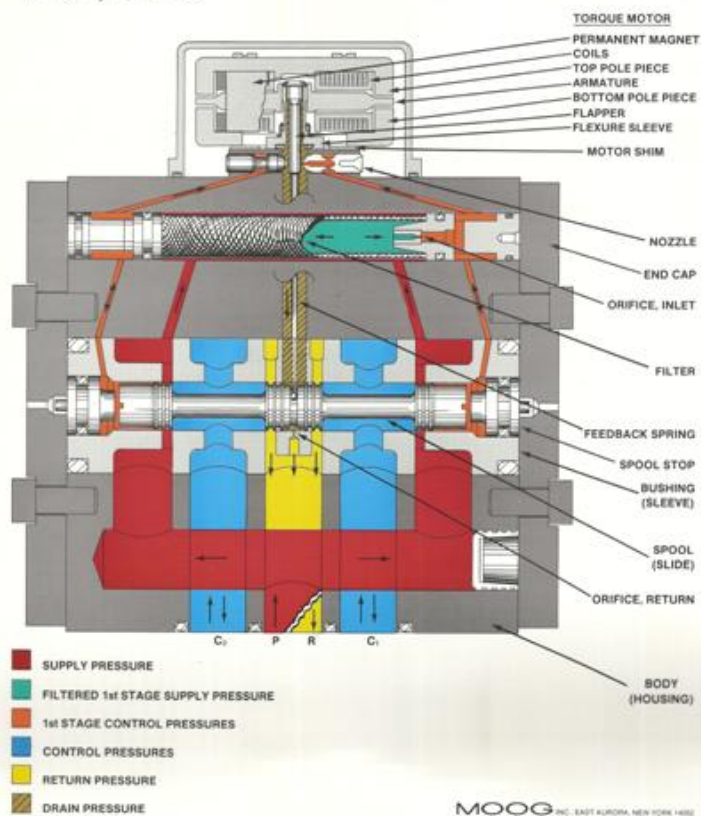
For highly accurate control as in aerospace systems and some machine tools, a two- stage electrohydraulic servo valve is used. (shown in figure)

In this valve, an electrical input signal operates a torque motor, which turns a flapper which runs between two nozzles > which varies the back pressures at two nozzles > backpressures act at either end of the main spool > which moves the spool and lets certain flow > which in turn moves the flapper at the nozzles in opposite direction to that produced by torque motor > which in turn changes the feedback pressures acting on spool > spool keeps on moving this way till flapper comes to the middle of nozzles, when the back pressures acting on spool are equal > spool movement stops.

With the above sequence of operations, it can be seen that magnitude of spool movement or of the corresponding flow is related to the input current or voltage signal to the servo valve.

These valves are highly accurate but cost can be very high ranging from Rs. 3 to Rs. 10 lakhs and higher.

Valve, Servo



Electrohydraulic servo system.

9-3 Electro-Hydraulic Two-Stage Servo Valves

Nearly all types of servo valves are based on common principles. Electro-hydraulic two-stage servo valves generally operate with force feedback. Given that valve pressure drop is constant, the valves control the output flow in proportion to the input signal. Therefore, they can be used to drive a hydraulic cylinder or motor at a speed proportional to the input current.

Figure 9.5 provides illustrations of an electro-hydraulic servo valve. The valve contains identical torque motors in parallel, which serve as a nozzle flapper amplifier with movable coils and nozzles. Coil displacement always determines the spool position. To ensure reliable pilot operation, the valve is provided with a filter prior to the pilot line, as well as a high-performance line filter prior to the valve inlet. Table 9.1 shows valve specifications, and Fig. 9.6 provides frequency response variations.

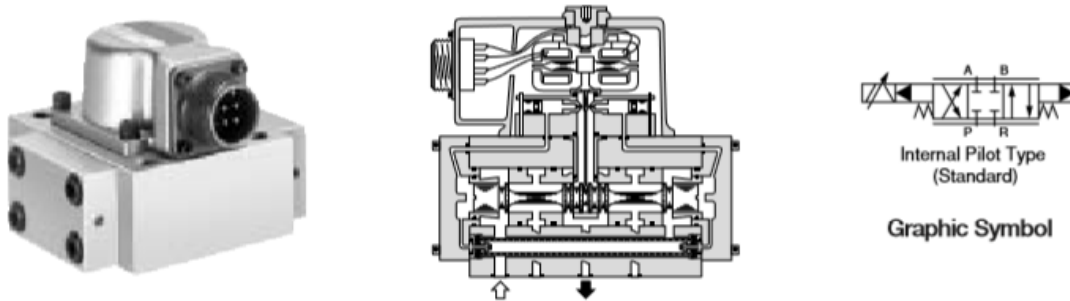


Fig. 9.5 Electro-Hydraulic Servo Valve

9-1 Servomechanism (Tracking Mechanism)

A servomechanism is an automatic control system designed to operate in accordance with input control parameters. The mechanism continuously compares the input signal to the feedback signal to adjust the operating conditions for error correction. Commercially available servo systems vary according to their methods for error detection, amplification, communication, and output.

Hydraulic servo systems have been widely applied in general industrial areas, as well as in the airline, maritime, and military industries. Servo systems, capable of automatic position, speed, and force (load) control with high accuracy and quick response, are used for high-speed injection molding, die-casting, rolling mill, press machines, industrial robots, simulators, testing machinery, and table feeders.

A hydraulic servo system consists of an actuator (hydraulic motor/cylinder), servo valves, sensors, and a servo amplifier, as shown in Fig. 9.1. Figure 9.2 shows a servo system applied to a high-speed vibration test machine.

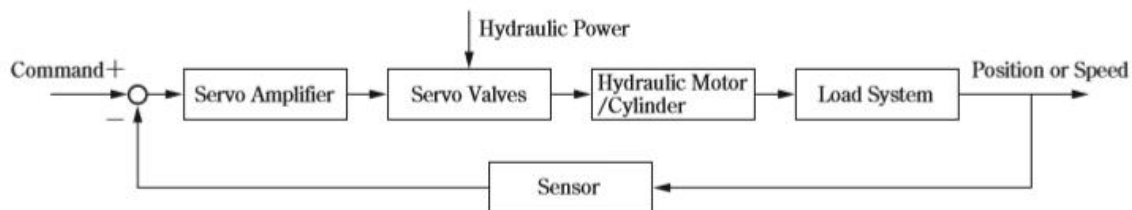


Fig. 9.1 Servo System Configuration

Table 4.2 Spool Types

Spool Type	Graphic Symbol	Valve and Spool (Neutral Position)	Function and Usage
"2" Closed-Center			Maintains the pump pressure and cylinder position in the neutral position. For the two-position type, each port is blocked during the spool transition, causing shock to the system line. This type requires due caution.
"3" Open-Center			Unloads the pump and floats the actuators in the neutral position. For the two-position type, each port is connected to the tank during the spool transition; thus, shock can be reduced.
"4" ABT Connected			Maintains the pump pressure and floats the actuator in the neutral position. The two-position type is used to maintain the system pressure during the spool transition. Shock is reduced compared to the type "2."
"40" ABT Connected, with Throttle			A variation of the type "4," having throttles between A to T and B to T. It can quickly stop the actuator.
"5" PAT Connected			Used to unload the pump in the neutral position and stop the actuator by feeding flow in one way.
"6" PT Connected (Closed during Transition)			Unloads the pump and maintains the actuator in the neutral position. It allows valves to be connected in serial.
"60" PT Connected (Opened during Transition)			A variation of the type "6." Each port is connected to the tank during the spool transition; thus, shock can be reduced.
"7" Center Opened, with Throttle			Mainly used for the two-position type; shock can be reduced during the spool transition.
"8" Two-Way			Maintains the pump pressure and cylinder position in the neutral position, similar to the type "2." Used as a two-way directional control valve.
"9" PAB Connected			Forms a differential circuit in the neutral position.
"10" BT Connected			Prevents one-way minor sliding of the actuator due to leak at the port P in the neutral position.
"11" PA Connected			Blocks one end and feeds flow from the other end to completely stop the actuator in the neutral position.
"12" AT Connected			Able to prevent the actuator from minor one-way sliding due to leak at the port P in the neutral position.